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Hydrodynamic Modeling of a Multi-Pulse X-Ray Converter Target for DARHT - II

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Abstract

In phase two of the Dual-Axis Radiographic Hydrodynamic Test facility (DARHT-II), four electron beam pulses of variable pulse length strike an X-ray converter target to produce time-resolved X-ray image. An important requirement for the converter target is to minimize the hydrodynamic expansion of the converter material so that there is enough material to generate the required X-ray dose for all four pulses. Minimizing the hydrodynamic expansion is also important from the standpoint of beam transport. If there is too much expansion of the converter material, the spot-size of the beam will deteriorate due to the charge neutralization of the beam by the target plasma. The beam spot size can also be deteriorated by backstreaming ions. However, this effect can be minimized by placing a barrier foil in front of the target. In this paper, we present a converter target design, based on the simulations using the radiation hydrodynamics code LASNEX and the Monte Carlo radiation transport code MCNP, that can produce the required X-ray dose for all four pulses with tolerable X-ray spot size variation. Our calculations also show that the barrier foil may block the backstreaming ions for all four pulses.

1 INTRODUCTION

Electron induction linacs, because of their kiloampere current capability, have been proposed for intense, precision multiple pulse X-ray sources for advanced X-ray radiography. In DARHT-II,[1-3] all the pulses are generated from a single linac. By using a fast kicker, one long pulse is sectioned into four pieces. Time-resolved X-ray images with millimeter spatial resolution of the objects under study can then be obtained.

The intense X-rays required to generated the image are obtained by focusing the electron beam to a millimeter-sized spot on a converter target placed approximately 1 m from the object under study. Hydrodynamic expansion must be minimized for multi-pulse targets for two reasons. First, since time-resolved images require multiple pulses striking the same target, the converter material must be well confined so that there is enough integrated line density for all pulses in order to generate the required X-ray doses. Second, good spatial resolution requires that the beam focal spot on the target remains small. The axial expansion of the target plasma must be minimized in order to reduce the beam-plasma interaction length. The spot size can also be deteriorated by the backstreaming ions.[4] The backstreaming ions can be stopped by placing a barrier foil in front of the target. These requirements set the constraints on the converter target design that is pivotal to the success for advanced X-ray radiography.

In this paper, we analyze a converter target and barrier foils, using the radiation hydrodynamics code LASNEX. The configuration presented here satisfies the confinement requirement for generating required X-ray and with tolerable X-ray spot variation. The calculations also show that the barrier foils can survive the heating caused by all four pulses.

The target configuration is presented in Sec. 2. LASNEX simulation model is presented in Sec. 3. Simulation results are presented in Sec. 4. The calculations for the heating of the barrier foils are discussed in Sec. 5. The results are summarized in Sec. 6.

2 TARGET CONFIGURATION

The configuration of the converter target is shown in Fig. 1. The converter material is made of foamed tantalum which is surrounded by a cylindrical tamper. The radius of the cylinder is increasing toward the downstream side of the target to prevent direct hitting of the tamper by the e-beam. (The resulting heating would cause the inner surface of the cylinder to expand toward the axis. This can create blockage to the X-ray path and consequently may cause unacceptable variation in the X-ray spot size.) The concept of using foamed target for multi-pulse X-ray generation was first suggested by Pincosy.[5] Other types of X-ray converter targets have also been studied by Livermore groups.[6,7]

Note that the reduction of line density is mainly from radial expansion. The use of foamed tantalum, instead of solid tantalum, is to reduce the pressure in the converter material to minimize the radial expansion. Furthermore, stretching the converter to a greater length using foamed material can provide additional radial confinement of the converter material heated to high temperature near the axis. On the other hand, foamed material provides no advantage in terms of reducing the axial expansion. This is because the front of the rarefaction wave expands at a velocity that is proportional to the speed of sound which is approximately independent of the density of the material.[8]

The converter material in the target shown in Fig. 1 has a density of 3.95 g/cm^2 and a length of 0.42 cm. The total line density is 1.66 g/cm^2. The cylinder around the foam serves the purpose of containing the radial expansion of the converter material as it is heated up by the electron beam. If the expansion is not contained radially, the density of the material will drop rapidly and this implies a rapid decrease of the line density. Preserving the line density is necessary to generate the required dose of radiation for all four pulses.

Our target is designed for electron beams with current of 2 kA and energy of 20 MeV. The full-width-half-maximum (FWHM) e-beam spot size at the target is 1.08 mm. The flat top portion of the pulse lengths are: 16, 16, 34 and 100 ns. Each pulse is accompanied by a 10 ns rise and a 10 ns fall. The X-ray spot size is measured at the 50% from the peak modulation transfer function (MTF).

3 LASNEX SIMULATION MODEL

In order to calculate the energy deposition correctly, we must take into account of the beam envelope expansion as the beam traverses the target. Because of scattering, the beam envelope increases rapidly. Note that this rapid expansion puts a constraint on the maximum length of the converter material. The beam envelope is calculated using an envelope equation, with a scattering term, that has the form[9]

$$\frac{\partial^2 R}{\partial z^2} - \frac{K}{\gamma_0 - Kz}\frac{\partial R}{\partial z} = \frac{\left[E_0^{\,2} + \frac{\langle\theta_t^{\,2}\rangle}{z_0}R^2\int_0^z \frac{dz'}{(\gamma - Kz')^2}\right]}{R^3}.$$

where

$$\langle\theta_t^{\,2}\rangle \equiv \frac{\alpha z_0}{\gamma_0^{\,2}}$$

$$\frac{\alpha}{\gamma^2} = \frac{4\pi N Z(Z+1)r_e^{\,2}}{\gamma^2\beta^4}\ln\frac{204}{Z^{0.33}}$$

$$K = \frac{\partial\gamma}{\partial z}$$

Here, β is the , E_0 is the rms emittance, γ is the Lorentz factor, γ_0 is the Lorentz factor of the beam at the entrance of the target, N is the number density, r_e is the electron radius, z is the axial location of the beam in the target, z_0 is the axial location where the beam encounters the target, and Z is the atomic number.

LASNEX updates this envelope equation at every cycle so that the beam envelope can be obtained as the density varies. Monte Carlo calculations show a larger envelope than that calculated using our envelope equation and therefore, LASNEX simulations over-estimate the temperature of the target and this results in an over estimate of the hydro expansion. This over-estimated hydro expansion provides us the performance margin.

During the first pulse, as the foamed tantalum is being heated by the e-beam, the tantalum first makes a transition into the multi-phase regime before entering the vapor phase near the end of the first pulse. To accurately model the temperature rise, we have created an equation-of-state (eos) table that properly takes into account of the increased specific heat capacity for tantalum in the multi-phase regime.

The energy deposition profiles for tantalum targets with various total line densities are plotted in Fig. 2. These energy deposition profiles as a function of distance traveled in the converter material are determined by Monte Carlo calculations.[10] The dependence on total line density is caused by the diffusive nature of secondary particles (electrons and photons). Note that the profile is peaked at the middle where it is hardest for particles to escape. Since the energy deposition is a function of total line density which decreases as the converter material expands, the profiles shown in Fig. 3 must be matched carefully with the corresponding total line density of the converter material as a function of radius to generate the deposition as a function of axial position for each of the pulses. This information together with the information for beam envelope expansion allow us to calculate the energy deposition in the converter material.

4 SIMULATION RESULTS

The density contours of the target hydrodynamic configurations at the beginning of each of the four pulses are shown in Fig. 3. Note that the hydrodynamic expansion near the beam-exit end of the target is considerably less than that near the beam-entrance end of the target. This effect is caused by beam envelope expansion. As the envelope expands, the energy deposited per unit volume at a given radius is greater near the entrance than at the exit of the target.

By the time when the fourth pulse arrives, the plume has expanded about 1 cm upstream. (The edge of the plume is defined at a density of 10^{-10} g/cm^2.) The beam over-focusing effect caused by this 1-cm long plume is insignificant. The amounts of electron energy deposited in the converter material for each of the four pulses are shown in Table I.

The radiation dose and X-ray spot size are from Monte Carlo calculations based on the density distributions reported here.[11] The comparison of the total radiation dose and the required dose output are shown in Table II, which shows that the radiation output from this target satisfies the requirement.

Note that in Table I, the energy deposited by the fourth pulse is about the same as the first pulse but the radiation dose from the fourth pulse is more than three times that of the first pulse as shown in Table II. This is because radiation output per electron does not fall off rapidly with the total line density until the total line density falls to about 20% of the initial line density of 1.66 g/cm^2

The X-ray spot sizes for all four pulses satisfy the requirement (see Ref. 9). For example, the 50% MTF spot size corresponding to the fourth pulse is only about 10% larger than that for the first pulse and the X-ray spot sizes for all four pulses are less than the required 50% MTF spot size of 2.1 mm.[11]

5 BARRIER FOIL

To minimize the effect of beam overfocusing by backstreaming ions, a barrier foil should be placed at a distance of about 4 cm or less upstream from the target. Earlier calculations on barrier foils had been performed by Kwan et al.[12] We have performed the heating of the foil by electron beams for foils placed at 4 cm upstream of the target. The FWHM e-beam spot size on the foil corresponding to 4 cm upstream of the target is 4.5 mm. We have calculated the heating for two types of materials, mylar and carbon. The thickness of the foils is 5 µm. The maximum temperatures reached by the mylar and carbon are 350 and 1000 °C, respectively. At the end of the fourth pulse, the density of mylar on axis has dropped by about 50%. However, the line density is essentially unchanged. Carbon hardly expands at all since the boiling temperature for carbon is relatively high, e.g. about 4800 °C. Therefore, both mylar and carbon foils should be able to stop backstreaming ions. However, recent studies by Davis[13] indicate that foils will start to release ions once the foils are heated to 400°C or above. This effect requires further studies.

6 CONCLUSION

The hydrodynamic expansion for the static X-ray converter target presented here is slow enough so that there is sufficient line density in the target to provide the required radiation dose for all four pulses. The X-ray spot sizes for all four pulse satisfies, i.e. less than, the required spot size and the variation in spot size from pulse to pulse is tolerable. The expansion of the plasma plume is not going to create noticeable beam overfocusing. The backstreaming ions can be stopped using foil barriers. Currently, the target presented here is chosen as the baseline target for the DARHT-II project.

7 ACKNOWLEDGEMENT

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Table I. Energy deposited

Pulse duration (flat top portion) (ns)	Energy deposited in the target (J)
16	129
16	106
34	120
100	141
total	496

Table II. Calculated vs required radiation dose

	Pulse 1	Pulse 2	Pulse 3	Pulse 4
On-axis required total radiation dose (Rad in air)	130	130	280	650
On-axis calculated total radiation dose (Rad in air)	248	247	386	846

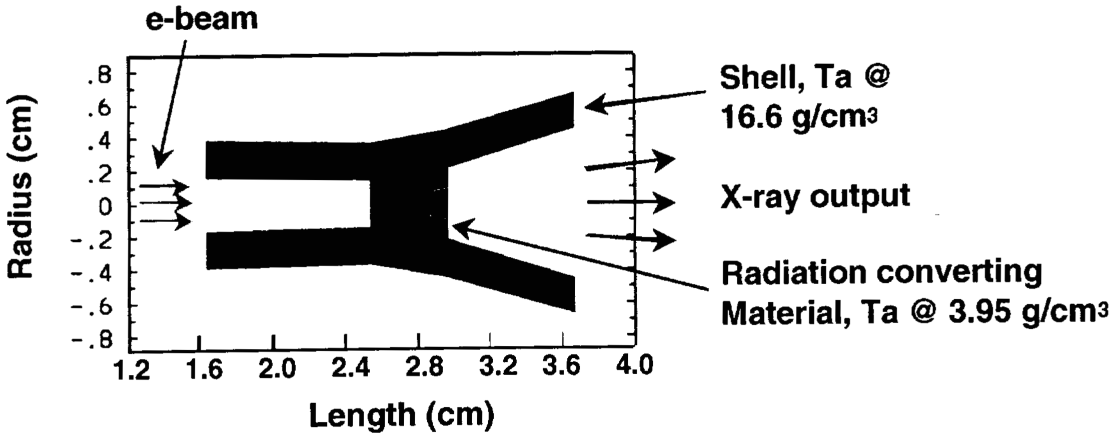

Fig. 1 Configuration of the static converter target

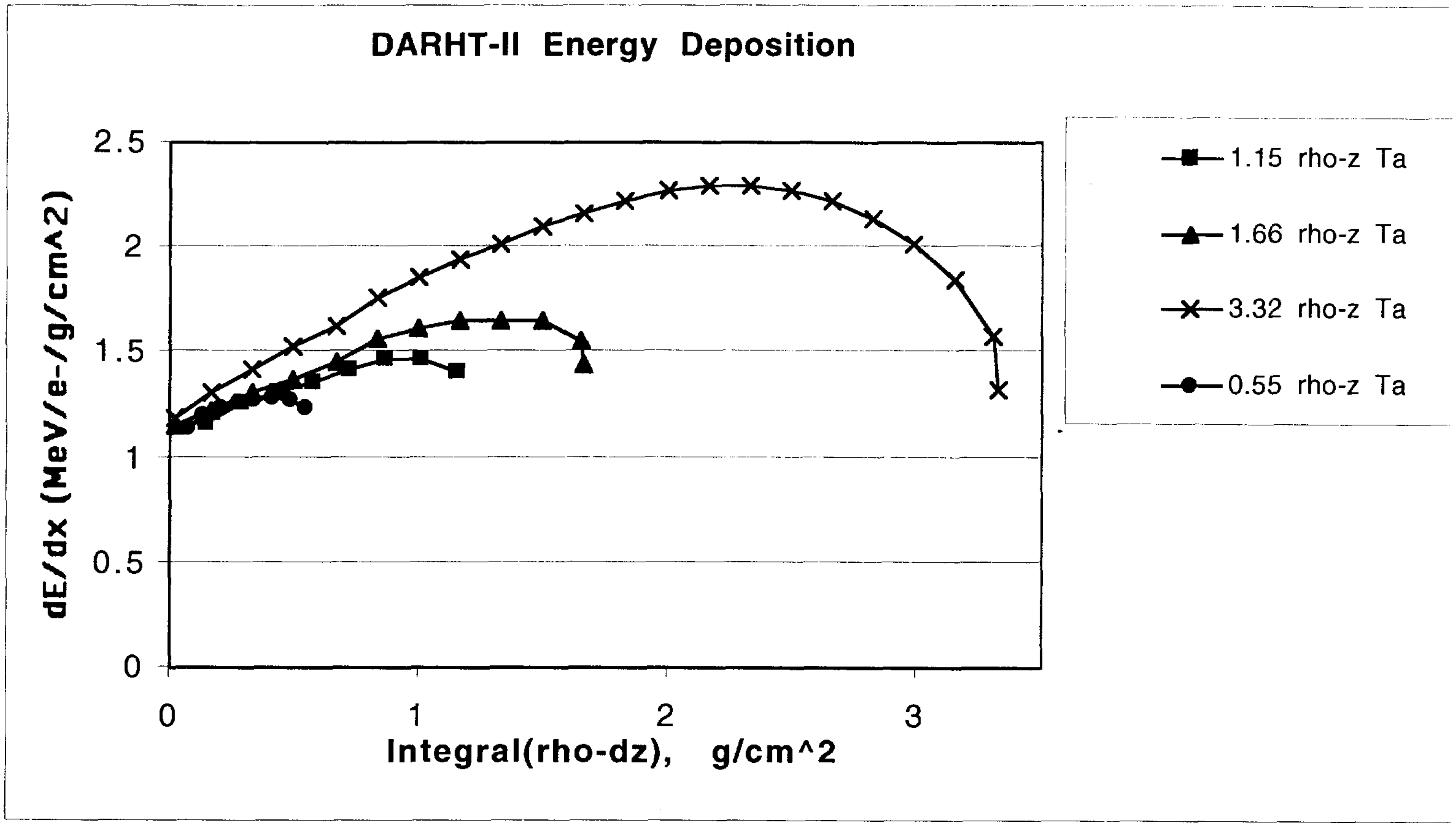

Fig. 2 Electron energy deposition as a function of line density for four different total line densities

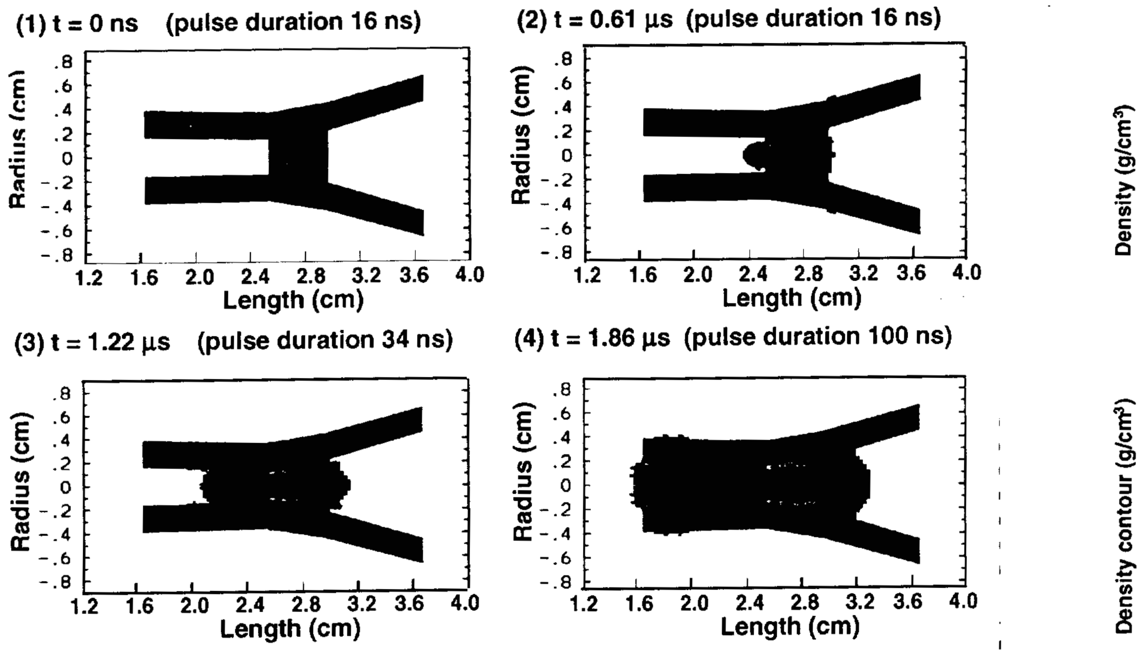

Fig. 3 Hydrodynamic configurations of the converter target at the Beginning of each pulse